J. Turner

Molecular Gas and Star Formation in Starbursts: A Closer Look

Molecular clouds are the fuel for starbursts. What conditions cause molecular clouds to create starbursts? Are high gas surface densities sufficient? What effects do starbursts have on surrounding molecular gas? The current state of our knowledge of star formation and gas links will be reviewed, and extrapolated to what upcoming observations in the far-IR and millimeter/submillimeter may reveal about the causes and effects of starbursts.

molecular gas & star formation: a closer look

Jean Turner UCLA

the next decade will reveal the molecular side of galaxies

the submillimeter window → dust & gas

Herschel, ALMA,

PdBI, SMA, CARMA, 30m, JCMT, APEX, ASTE, LMT

high resolution imaging & wide-field mapping + continuum or spectroscopy to $R=10^6$

important observations for starbursts

CO emission

dust emission from z=0 → ?

free-free emission (3, 1mm = “sweet spot”)

other molecules… HCN on

fine structure lines of atoms in submm

H_2 warm, radiatively excited

first excited level E/k ~500K — excited via shocks or fluorescence

pure rotational lines from Spitzer

in starbursts: warm gas is 10%* of total in SB, 35%* in Seyferts

in ULIRGs: warm gas is typically ~1%* of the cold gas mass, $10^8 - 10^{10}\ M_{sun}$

rigapoulou et al. 2002, higdon et al. 2006, armus +2006

* T-dependent

CO cool gas tracer

tracer of all cool molecular gas, abundance 10^{-4} H_2

first excited level E/k = 5.5K

low dipole moment → collisionally excited, thermal

optically thick → $n_{crit} \sim 100\text{-}200\ cm^{-3}$

$$T_b = T_{ex} = T_k$$

self-shielding: $A_v \sim 2$, mixed with C I

HCN/HNC dense cool clouds

tracer of dense, cool gas

first excited state E/k ~ 5K

high dipole moment: $n_{crit} \sim 10^5\ cm^{-3}$

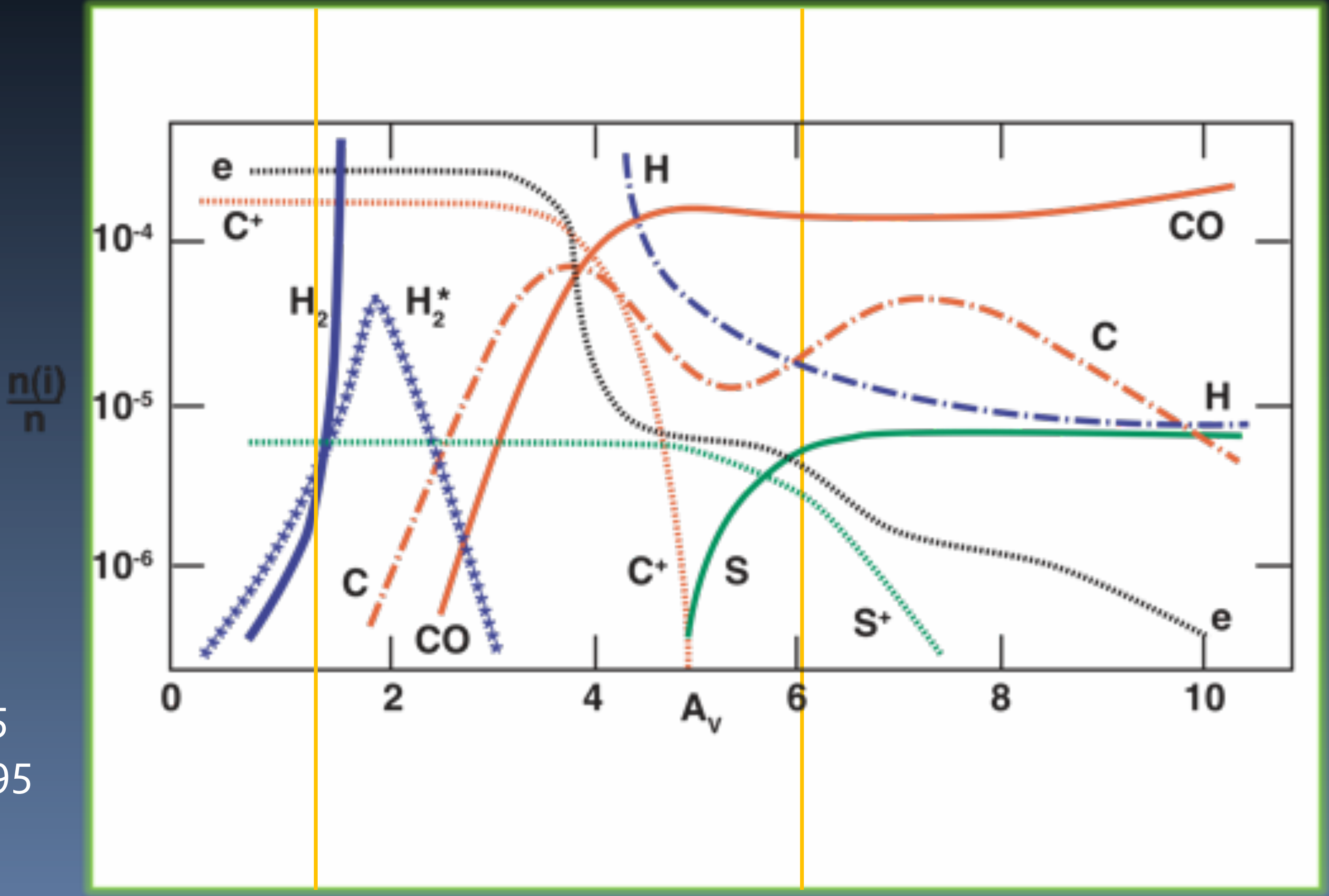
high density tracer, should be well-correlated with star formation

caveat: IR pumping possible X-ray can affect chemistry & abundances gracia-carpio et al. 2006, aalto et al. 2007

radiative feedback

Photo
Dissociation
Regions

PDRs



Tielens &
Hollenbach 1985
Wolfire et al. 1995

Tielens 2006 book

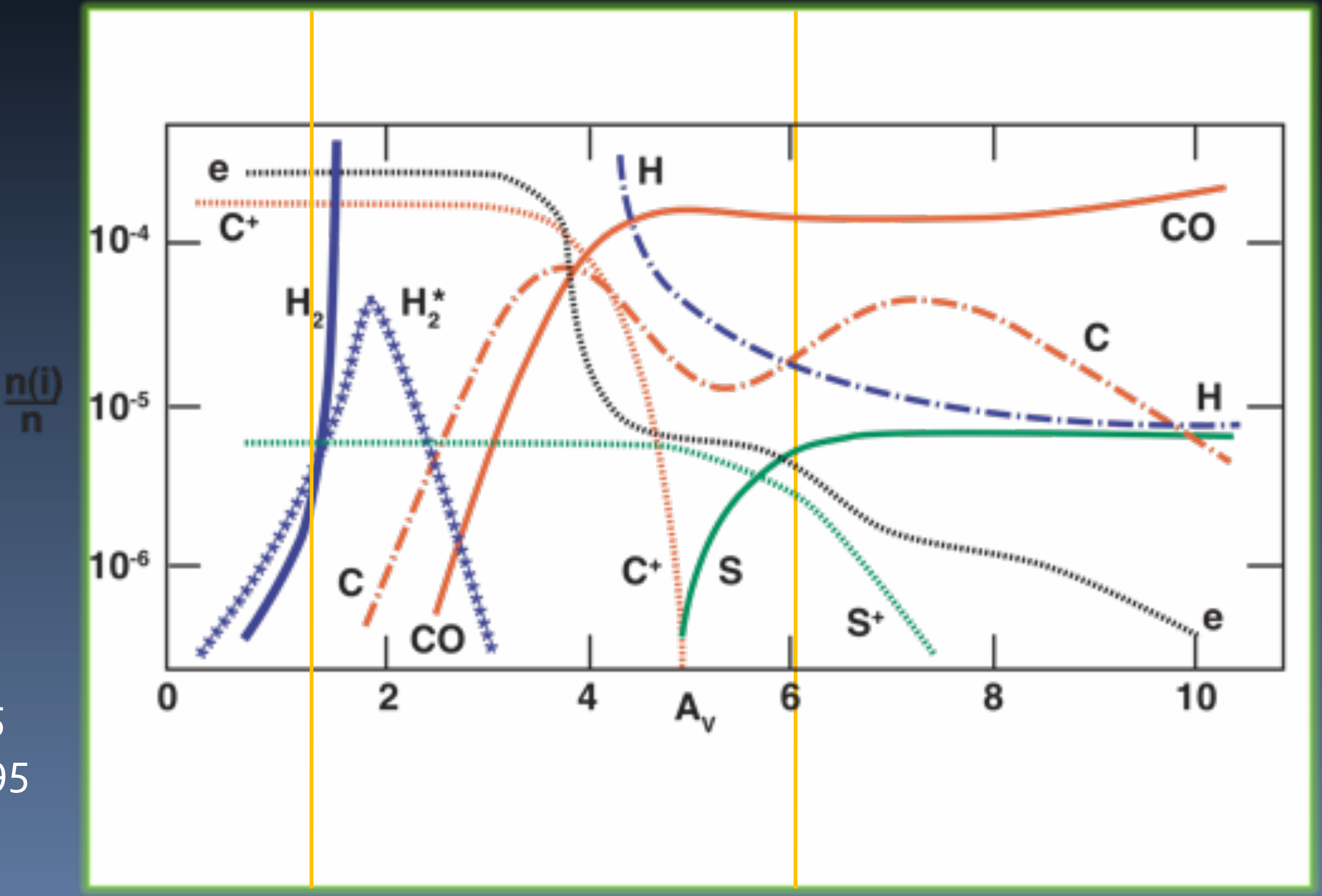
radiative feedback

Photo
Dissociation
Regions

PDRs

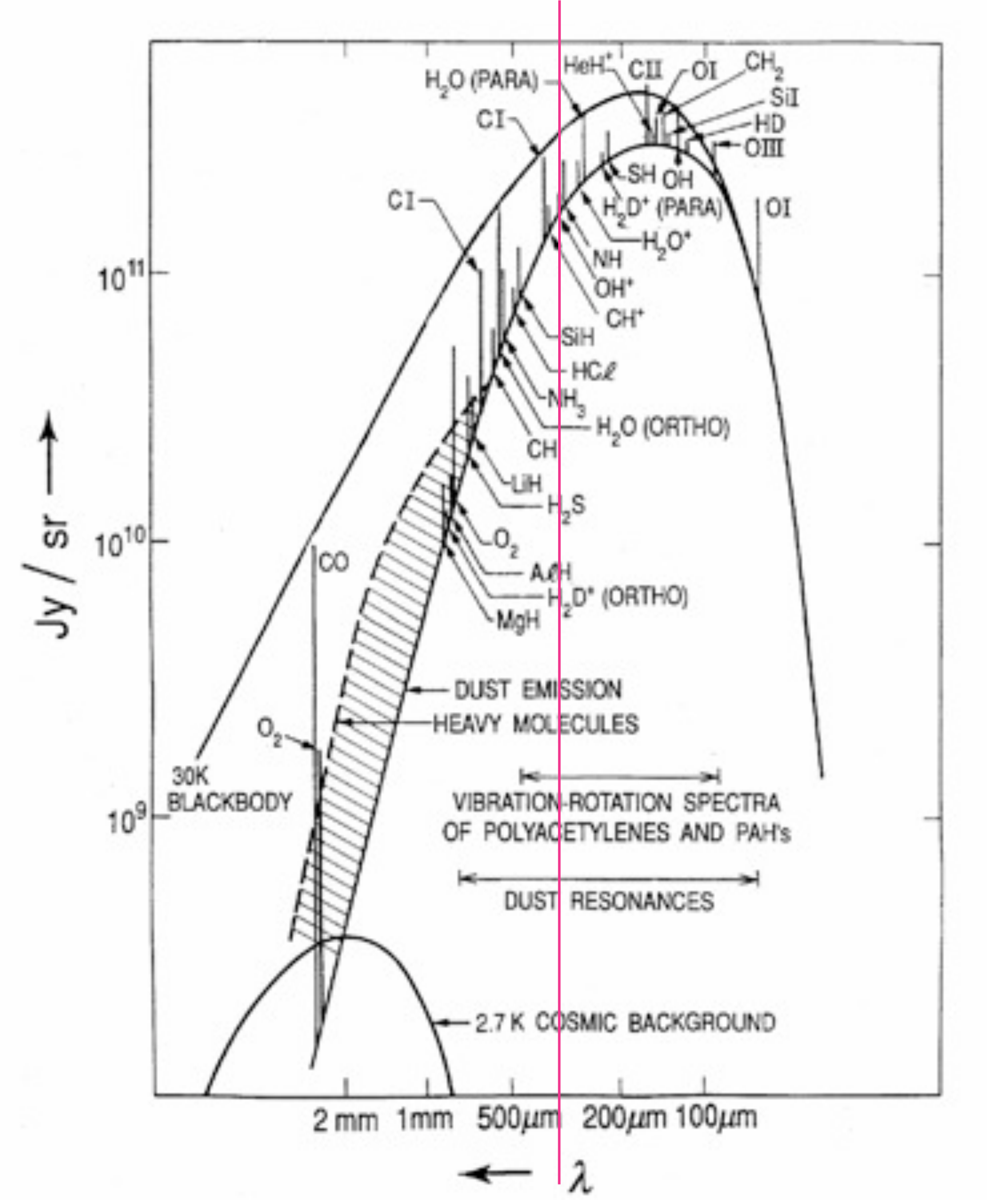
Tielens &
Hollenbach 1985
Wolfire et al. 1995

Tielens 2006 book



90% of CO emission is from PDRs

chemical feedback: 30K cloud



“XDR” X-ray dominated region

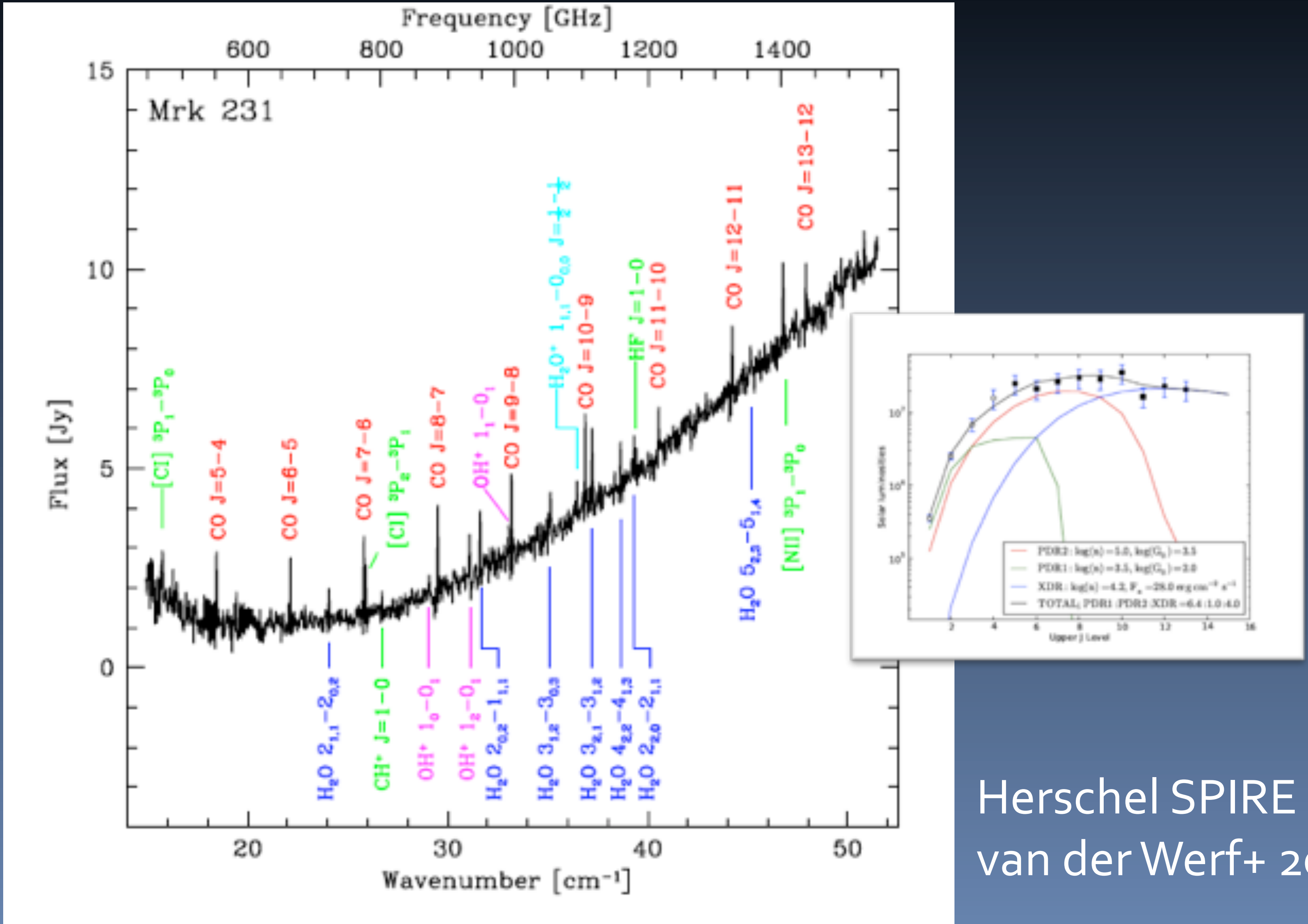


Fig. 1. SPIRE FTS spectrum of Mrk 231. Line identifications are given in red for CO lines, in blue for H_2O, in magenta for OH^+, in cyan for H_2O^+, and in green for the remaining lines.

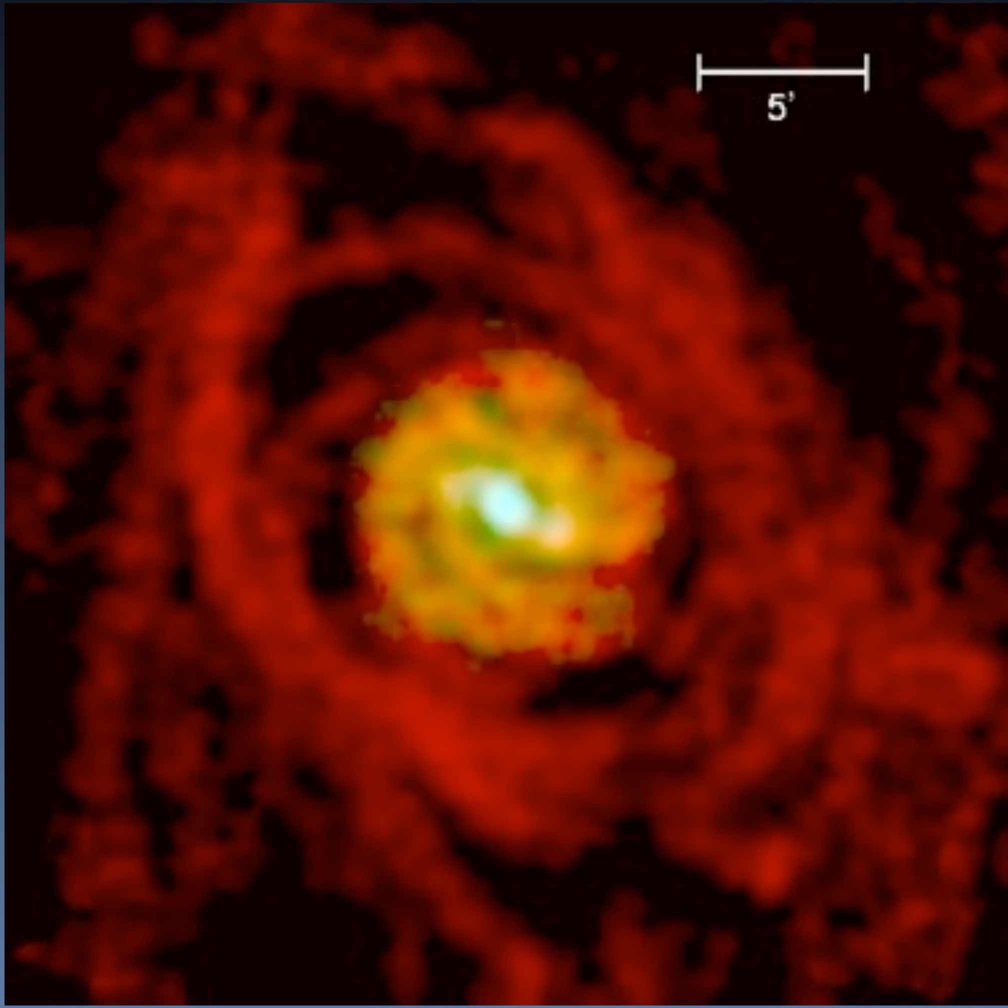
Herschel SPIRE
van der Werf+ 2010

molecular gas is star-forming gas

CO disks = star-forming parts of spirals

M83

2MASS JHK Jarrett et al. 2003



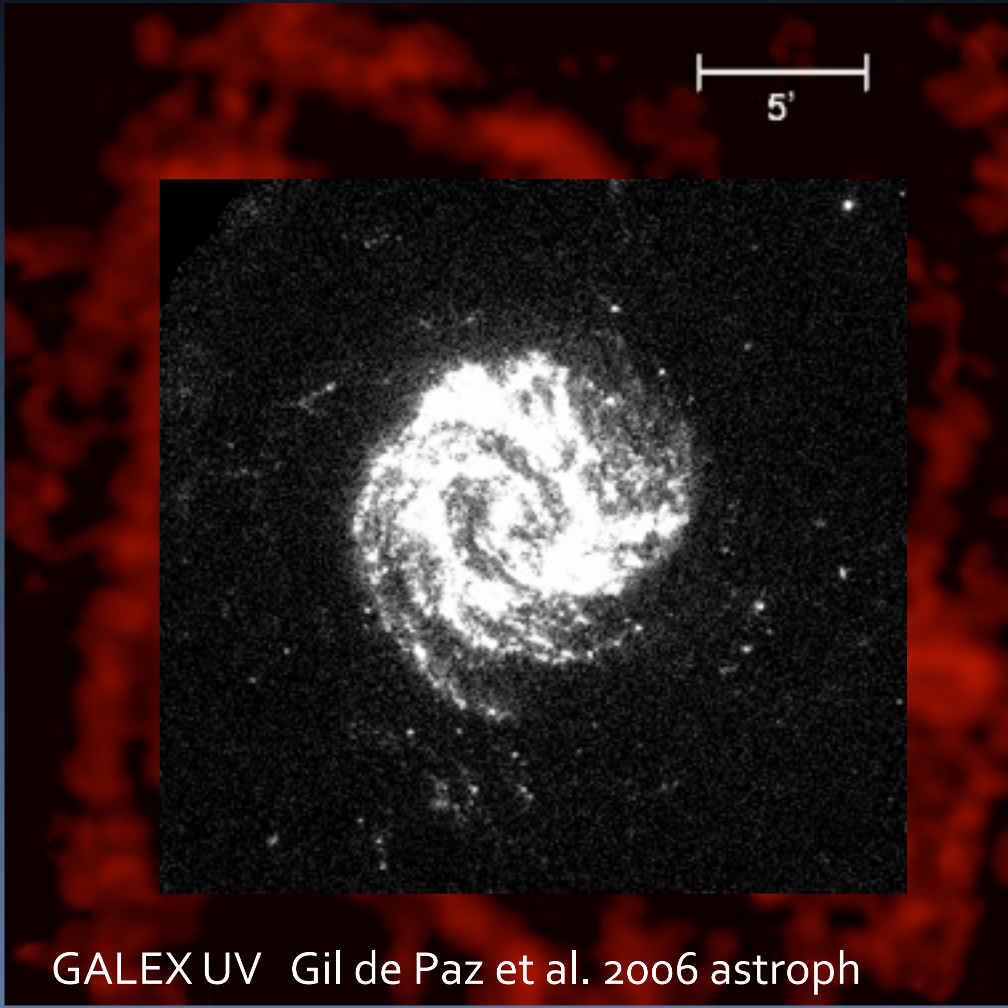
HI gas in red Tilanus & Allen

CO in green: NRAO 12m Telescope Crosthwaite et al. 2002

CO disks = star-forming parts of spirals

M83

2MASS JHK   Jarrett et al. 2003



GALEX UV   Gil de Paz et al. 2006 astroph

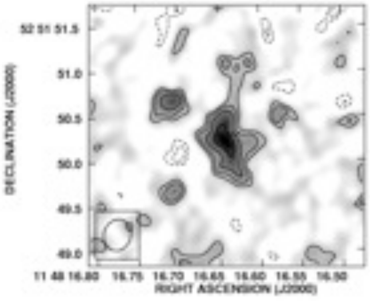
HI gas in red Tilanus & Allen

CO in green: NRAO 12m Telescope Crosthwaite et al. 2002

GALEX finds star formation in HI?

young stars (ultraviolet)
red: gas (radio)

CO and CII detected in z=6.42 galaxy



SDSS J114816.64+525150.3 highest redshift QSO 870 Myr universe

two peaks, separation 1.7 kpc; 2.5 kpc total extent

$M_{H_2} \sim 1 \times 10^{10} M_{sun}$

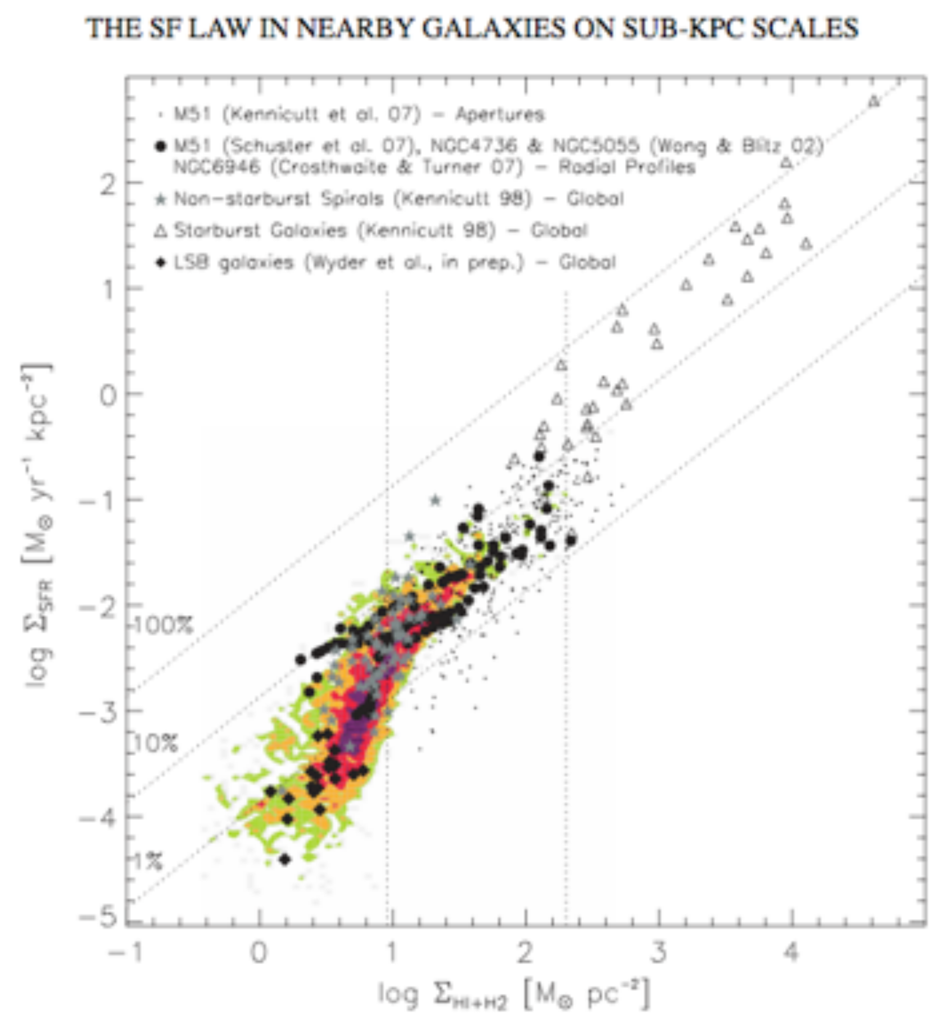
dynamical mass 5-6 x 10^{10} M_{sun}

CII: SFR~ 3000 M_{sun}/yr

for abundant CO need metallicities ~0.03-0.1 solar

norman & spaans 1997

star formation law for local spirals



bigiel et al. 2008

caveat: local galaxies

star formation (in)

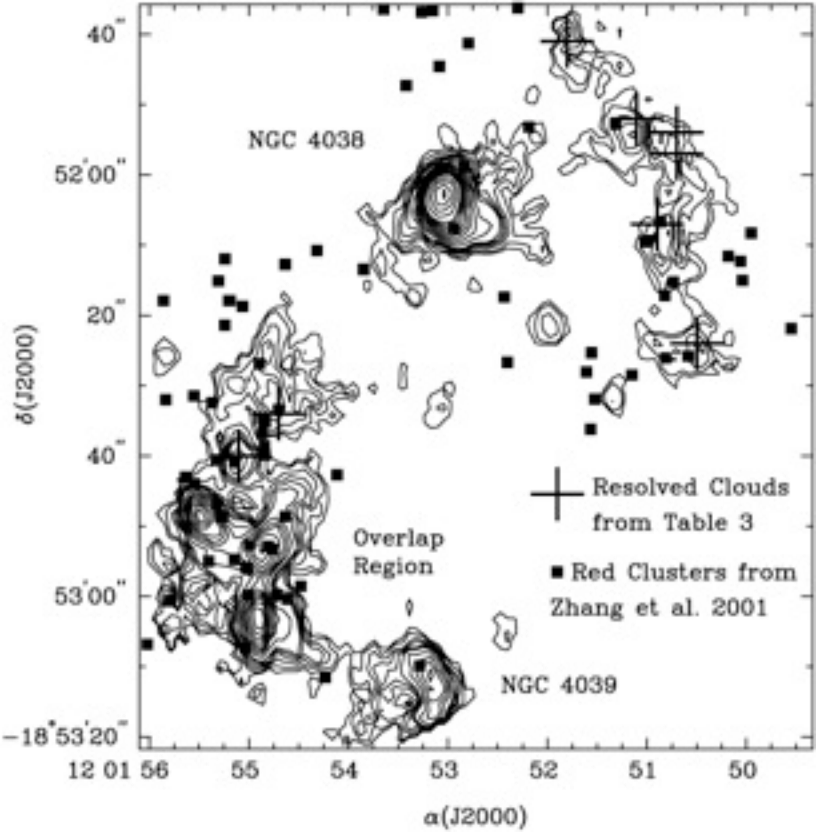
SFE

galactic SFE ~1% on GMC scales

lada, dearborn, margulis 1984

cluster SFE (Orion) ~10%

SFE: $\eta = M_{stars}/(M_{stars} + M_{gas})$



CO image from OVRO Wilson+03

MH2 = 1.5×10^{10} M_{sun} Gao+01

the Antennae

η ~1%, Gao+01

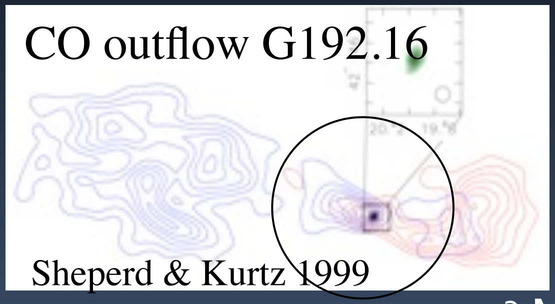
star formation in molecular clouds is regulated by turbulence

at any given time, 1% of the “cores” (0.1 pc) in a 30-50 pc GMC are collapsing

McKee, Padoan, Elmegreen, Tan, Krumholz

variation in efficiency is a factor of > 100 in local galaxies

challenge to theorists: how to form a SSC: what's within 1 pc of an O star?

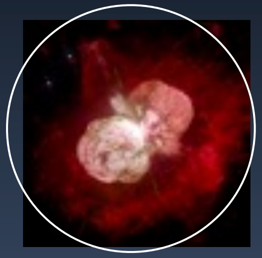


CO outflow G192.16

Sheperd & Kurtz 1999

age ~ 0.5 Myr

$10^{-3}\ M_{\odot}$/yr



Morse et al. 1996

LBV

$10^{-5}\ M_{\odot}$ /yr

400 km/s

age: ~1 Myr

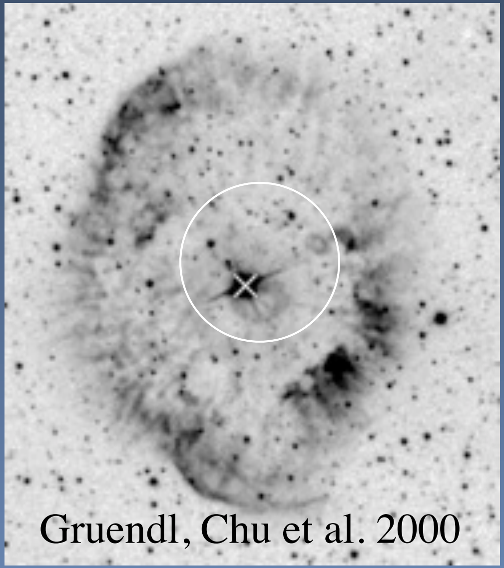
WR Ring Nebula

$10^{-5}\ M_{\odot}$/yr

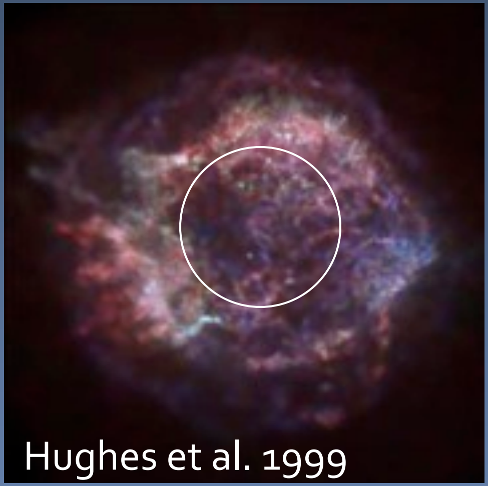
100 km/s

age:

2-3 Myr



Gruendl, Chu et al. 2000



Hughes et al. 1999

SNR

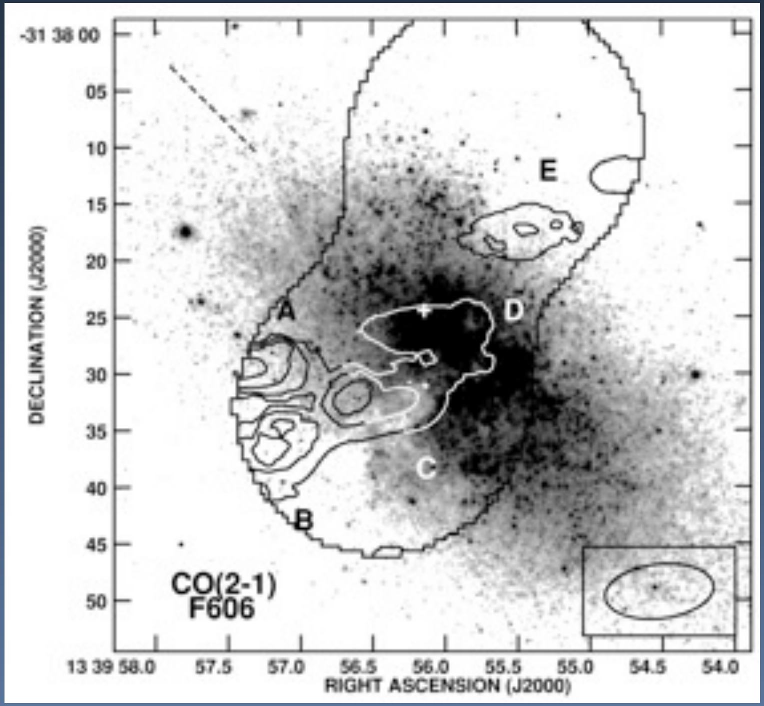
10,000 km/s

age:

3-10 Myr

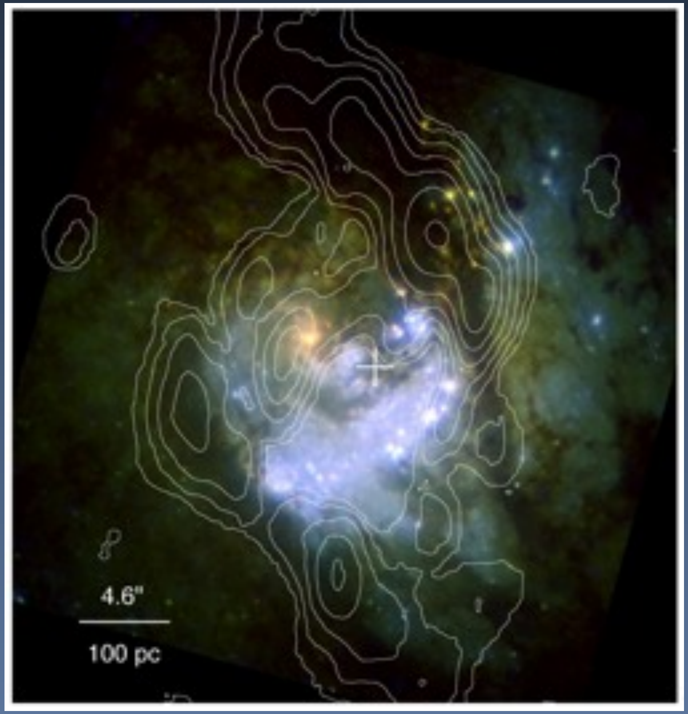
two local starbursts, 10^9 L_{sun}

NGC 5253



$M_{H_2} = 10^6\ M_{sun}$

NGC 5236 (M83)

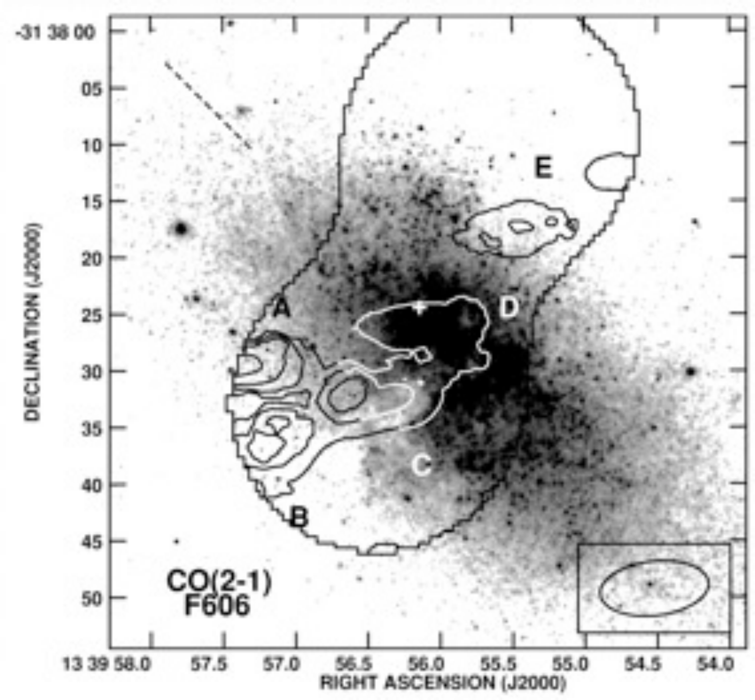


$M_{H2} = 10^8\ M_{sun}$

star formation has not always been inefficient...

bound clusters require $\eta \geq 50\%$

SFE: $\eta = M_{stars}/(M_{stars} + M_{gas})$



the Antennae are not forming globular clusters

η ~1%

ngc 5253 might

η ~75%

star formation (in)efficiency

star formation is inefficient, η~ 1%-10% in local galaxies

~50% efficiency needed for bound clusters: 10 Gyr globular clusters ➔ efficiencies were higher in early universe?

there are many ways to prevent clouds from forming stars

X

X_{co}! the good...

$X_{co} = I_{co}/n_{H_2} = 2 \text{ x } 10^{20}\ \mathrm{cm}^{-2} / (\mathrm{Jy/km/s})$ in Galaxy

empirical relation, good to factor ~2 (Y-rays)

strong et al. 1988

X_{co}! the good...

$X_{co} = I_{co}/n_{H_2} = 2 \times 10^{20}\ \mathrm{cm}^{-2} / (\mathrm{Jy/km/s})$ in Galaxy

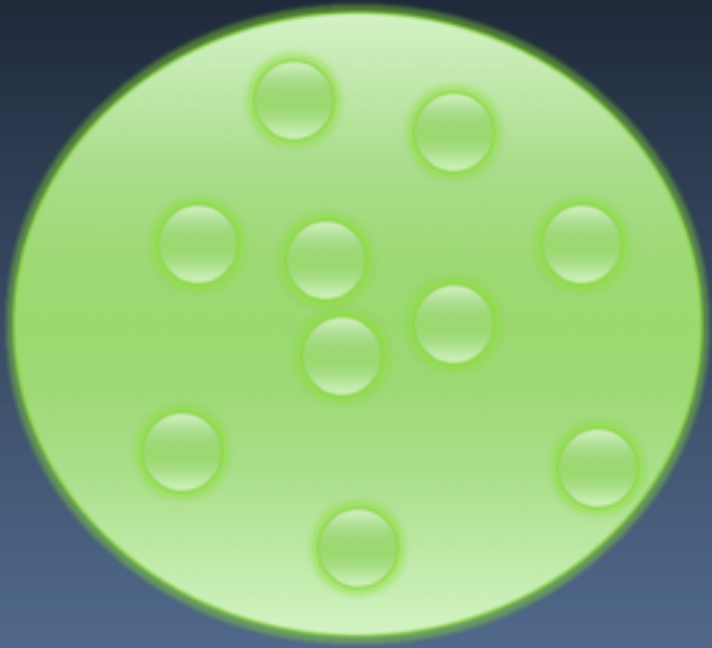
empirical relation, good to factor ~2 (Y-rays)

strong et al. 1988

explanation: GMCs appear to be in ~virial equilibrium, turbulent support

solomon et al. 1987

X_{co} arises in virialized, turbulent



1. size-linewidth relation
   Larson 1981
2. optically thick line profiles are Gaussian
   evans & zuckerman 1974
3. CO & CI have similar properties

GMCs are porous

X_{co}! the good...

$X_{co} = I_{co}/n_{H_2} = 2 \times 10^{20}\ \mathrm{cm}^{-2} / (\mathrm{Jy/km/s})$ in Galaxy

empirical relation, good to factor ~2 (Y-rays)

strong et al. 1988

explanation: GMCs in ~virial equilibrium, turbulent support

solomon et al. 1987

since X_{co} is a dynamical mass, not directly dependent on abundance

maloney & black 1988

Xco! ...the bad and the ugly

X_{co} is 3-4 times LOWER (overestimates H_2 mass) in Arp 220 & ULIRGS (“starburst conversion factor”)

downs & solomon 1993

X_{co} is 3-4 times LOWER (overestimates H_2 mass) in centers normal galaxies in the local universe, including our own

dahmen et al. 1993, meier et al. 2001, 2002, 2004, 2010

X_{co} is a factor of ~2-3 times LOWER (underestimates gas mass) in Magellanic clouds, but normal in other starburst dwarfs

verter & hodge 1995, wilson 1995, meier+02, bollato+08

Xco! ...the bad and the ugly

CO is a dynamical tracer of mass

when the dynamics of the gas do not reflect virial cloud dynamics, the mass will be off

tidal effects are important in galactic centers, although clouds are very dense there

chemistry

detected interstellar molecules

H_2 HD H_3+ H_2D+

CH CH^+ C_2 CH_2 C_2H $*C_3$

CH_3 C_2H_2 C_3H(lin) c-C_3H $*CH_4$ C_4

c-C_3H_2 H_2CCC(lin) C_4H $*C_5$ $*C_2H_4$ C_5H

H_2C_4(lin) $*HC_4H$ CH_3C_2H C_6H $*HC_6H$ H_2C_6

$*C_7H$ CH_3C_4H C_8H $*C_6H_6$

OH CO CO+ H_2O HCO HCO+

HOC+ C_2O CO_2 H_3O+ HOCO+ H_2CO

C_3O CH_2CO HCOOH H_2COH+ CH_3OH CH_2CHO

CH_2CHOH CH_2CHCHO HC_2CHO C_5O CH_3CHO c-C_2H_4O

CH_3OCHO CH_2OHCHO CH_3COOH CH_3OCH_3 CH_3CH_2OH CH_3CH_2CHO

$(CH_3)_2CO$ $HOCH_2CH_2OH$ $C_2H_5OCH_3$ $(CH_2OH)_2CO$

NH CN N_2 NH_2 HCN HNC

N_2H^+ NH_3 $HCNH^+$ H_2CN HCCN C_3N

CH_2CN CH_2NH HC_2CN HC_2NC NH_2CN C_3NH

CH_3CN CH_3NC HC_3NH^+ $*HC_4N$ C_5N CH_3NH_2

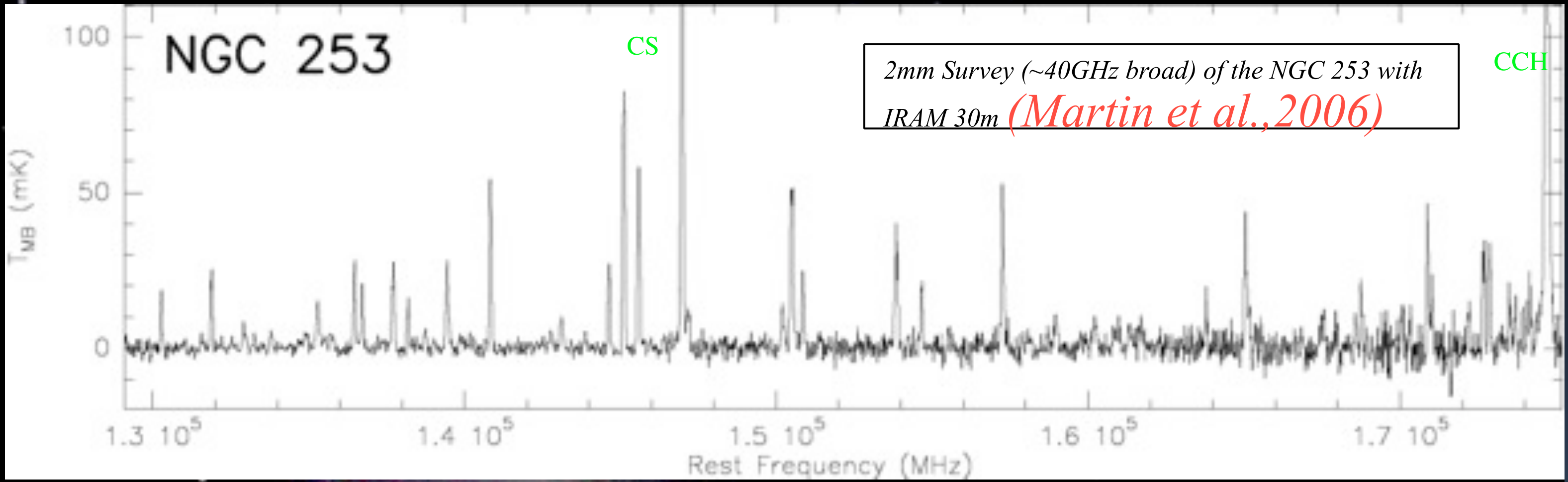
CH_2CHCN HC_5N CH_3C_3N CH_3CH_2CN HC_7N CH_3C_5N? HC_9N $HC_{11}N$

NO HNO N2O HNCO NH2CHO

SH CS SO SO+ NS SiH

*SiC SiN SiO SiS HCl *NaCl

*AlCl *KCl HF *AlF *CP PN



2mm Survey (~40GHz broad) of the NGC 253 with IRAM 30m (Martin et al.,2006)

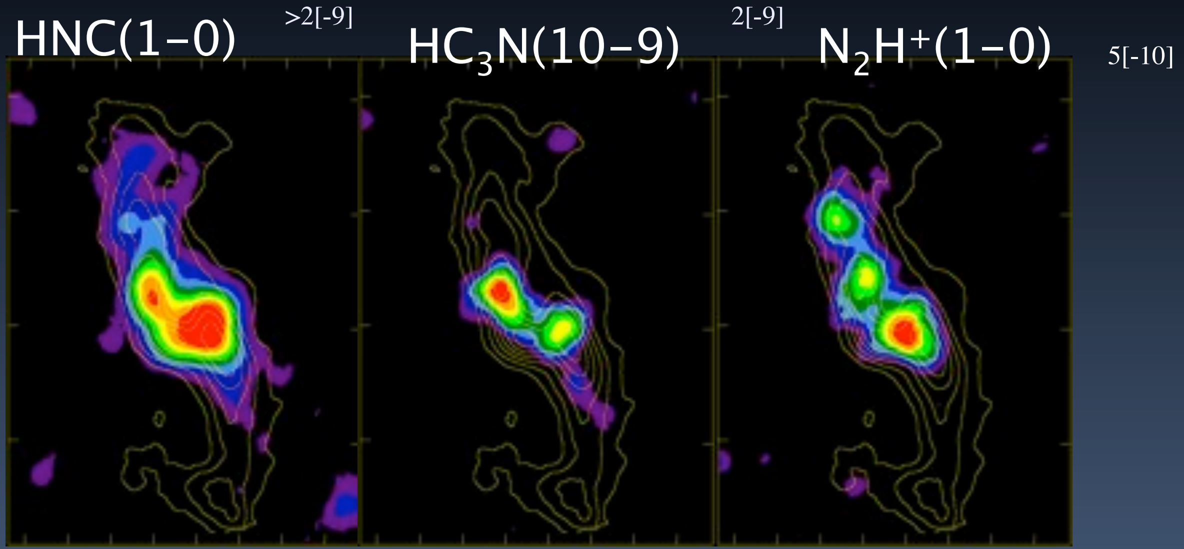
first unbiased line survey in a galaxy IRAM: 129.1 - 175.2 GHz @ dv ~ 9 km/s

IRAM Pico Veleta

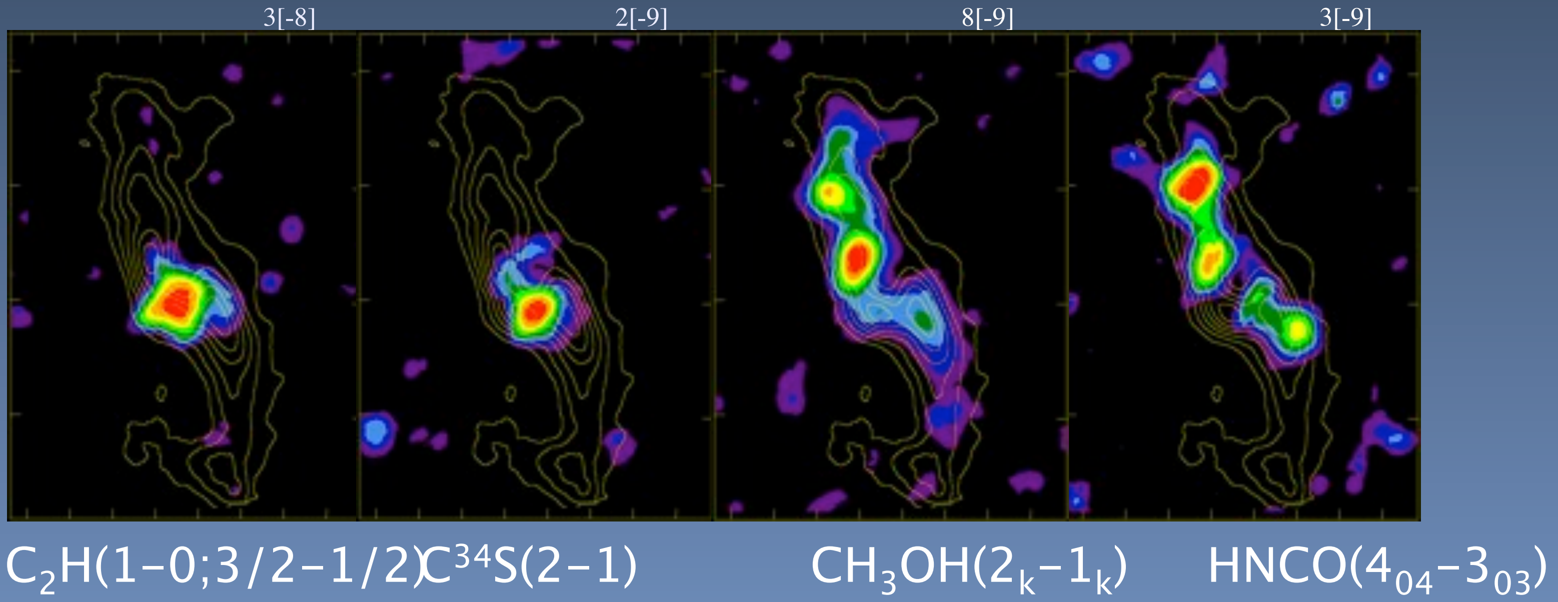
2MASS - Jarrett

chemical feedback: imaging chemistry

IC 342

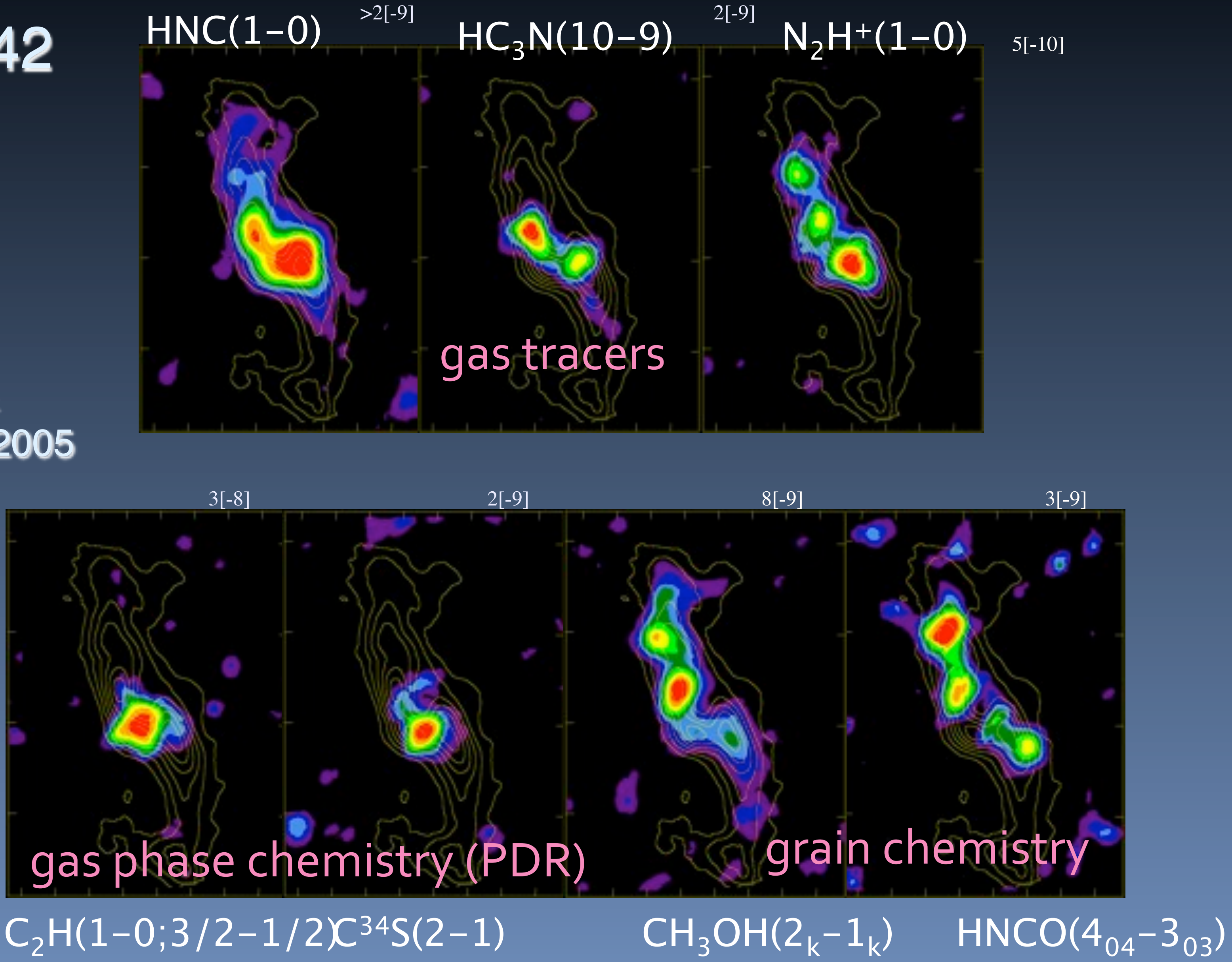


Meier &
Turner 2005



chemical feedback: imaging chemistry

IC 342



Meier &
Turner 2005

chemical diagnostics

shocks: SiO, HNCO

PDRs & high radiation fields: HCN, C_2H, HNC

XDRs: high J CO, HNC, HCN

X-rays more efficient at gas heating and less efficient at dissociation

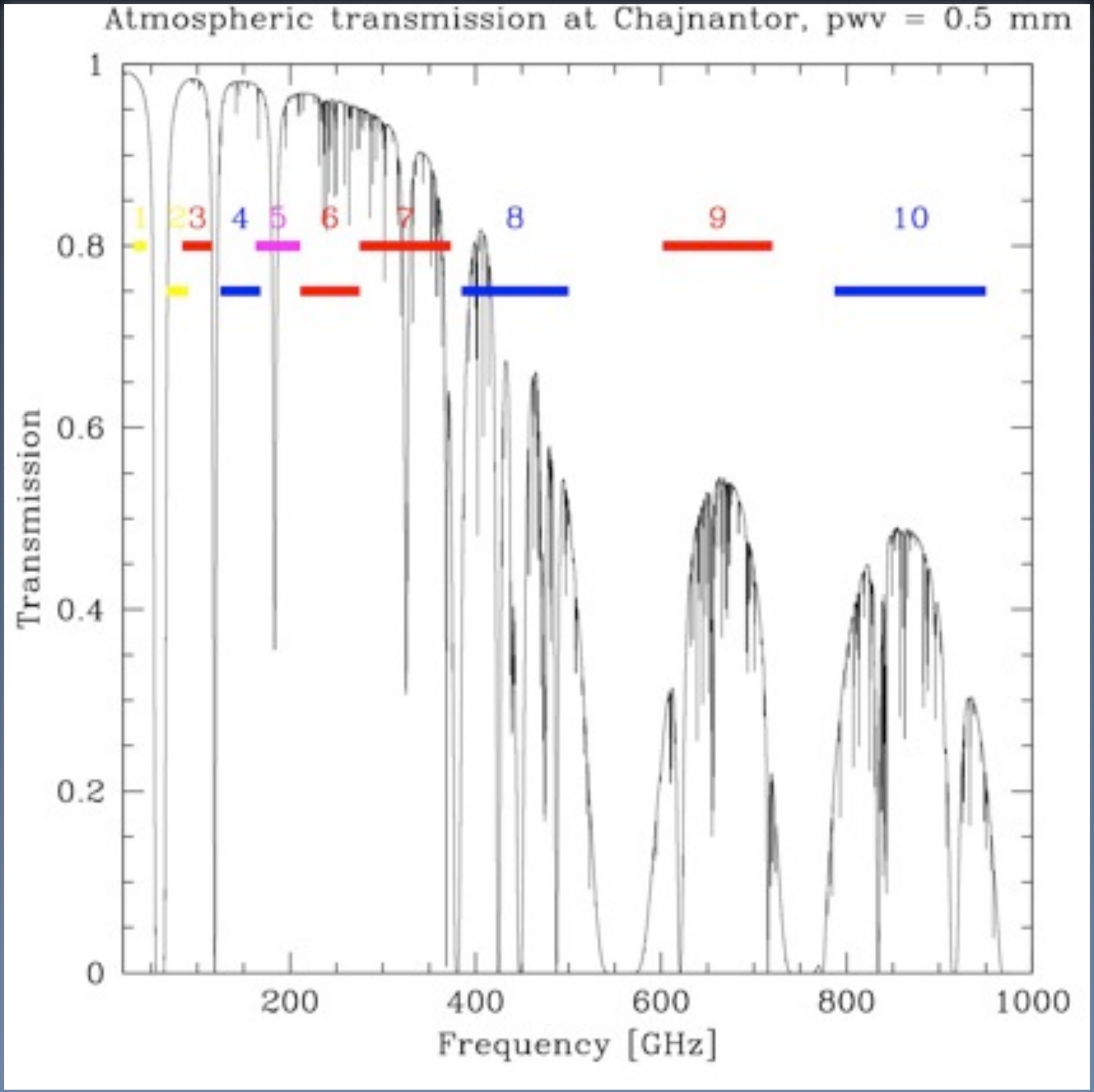
ALMA

ALMA: North America, Europe, Japan/East Asia

50+4 12-m antennas
ACA: 12 7-m antennas

First ACA 12m – Dec 2007, 7m – Nov 2008

alma

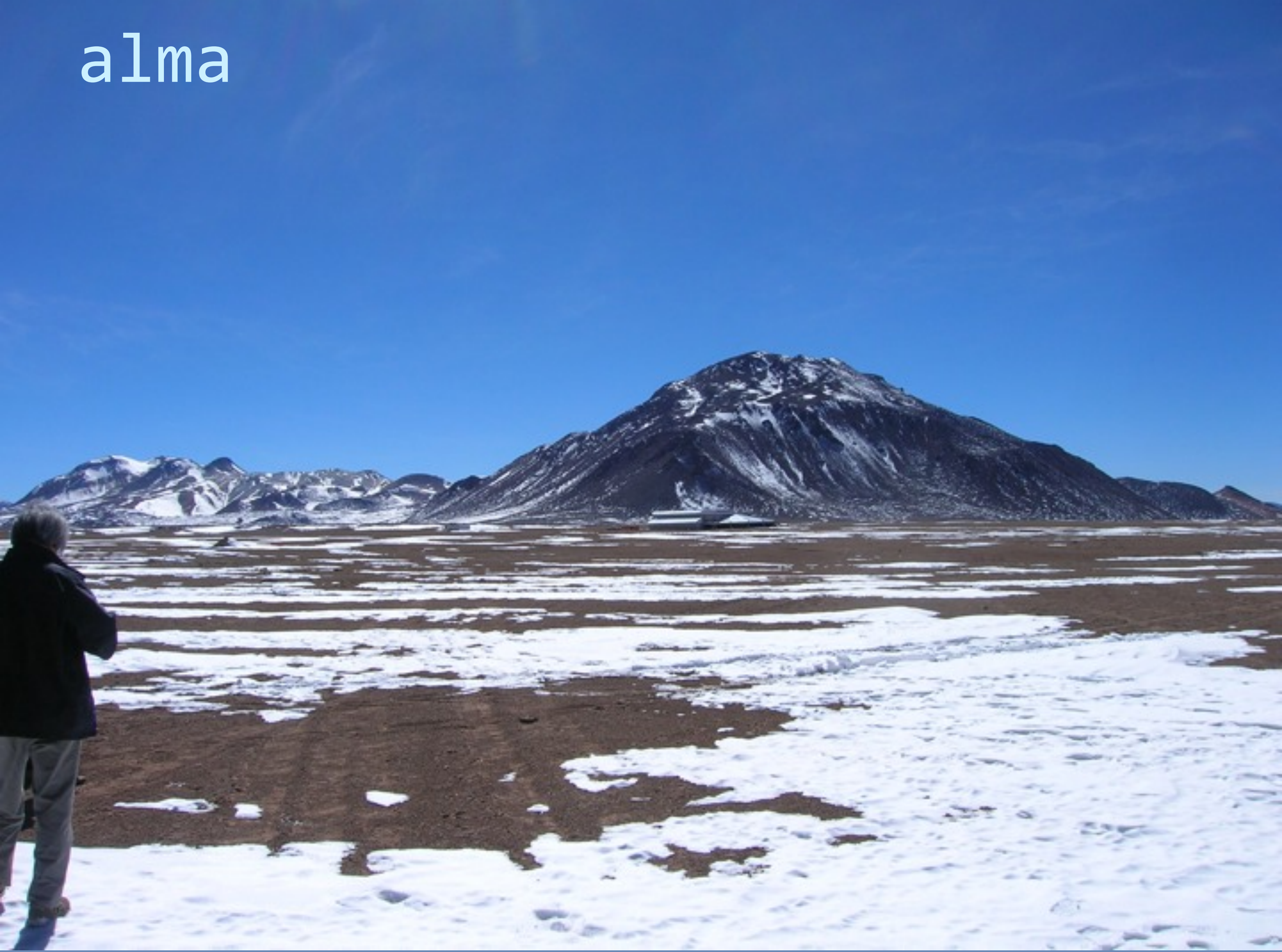

Atmospheric transmission at Chajnantor, pwv = 0.5 mm
Transmission
Frequency [GHz]
0
0.2
0.4
0.6
0.8
1
200
400
600
800
1000
1
2
3
4
5
6
7
8
9
10

alma design goals

1. detect CO in an L* galaxy at z=3.

- detect molecular lines in a protoplanetary disk with resolution 1 AU out to d=150 pc.
- imaging to match HST or AO, 0.1” resolution, high fidelity.

alma



AOS Technical Building – July 2007

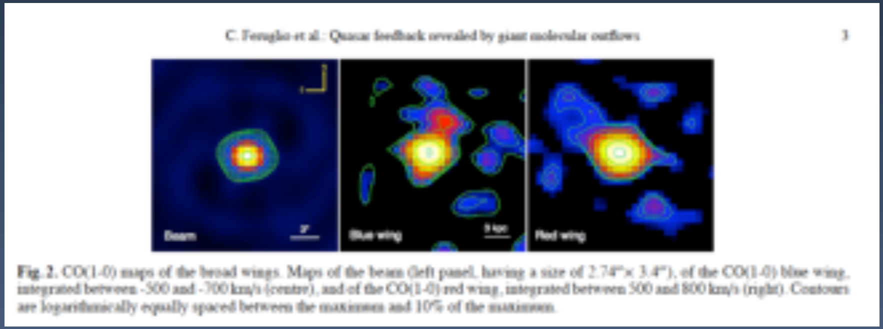
alma

5 telescopes at high site, adding ~1/month

awesome feedback!

AGN feedback on molecular gas

massive CO outflow observed in Mrk 231:
~600-2000 M_{sun}/yr,   1500 km/s FWZI



C. Feruglio et al.: Quasar feedback revealed by giant molecular outflows 3

Fig. 2. CO(1-0) maps of the broad wings. Maps of the beam (left panel, having a size of 2.74"× 3.4"), of the CO(1-0) blue wing, integrated between -500 and -700 km/s (centre), and of the CO(1-0) red wing, integrated between 500 and 800 km/s (right). Contours are logarithmically equally spaced between the maximum and 10% of the maximum.

Fischer et al. 2010
Feruglio et al. 2010

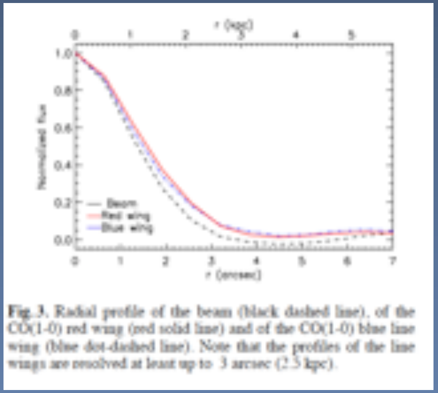
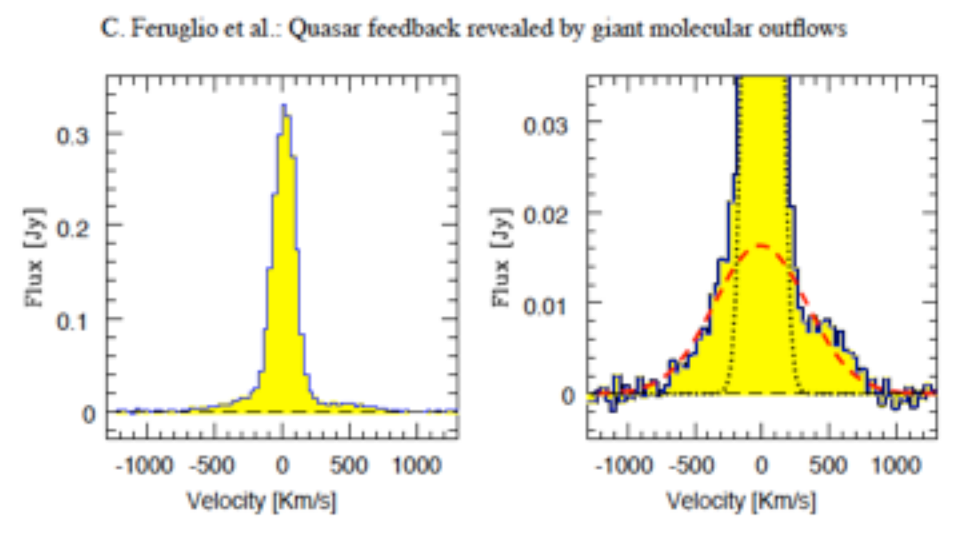


Fig. 3. Radial profile of the beam (black dashed line), of the CO(1-0) red wing (red solid line) and of the CO(1-0) blue line wing (blue dot-dashed line). Note that the profiles of the line wings are resolved at least up to 3 arcsec (2.5 kpc).



C. Feruglio et al.: Quasar feedback revealed by giant molecular outflows

molecules in galaxies: summary

CO will still dominate: detectable to high z, good for kinematics, but X_{co} needs work

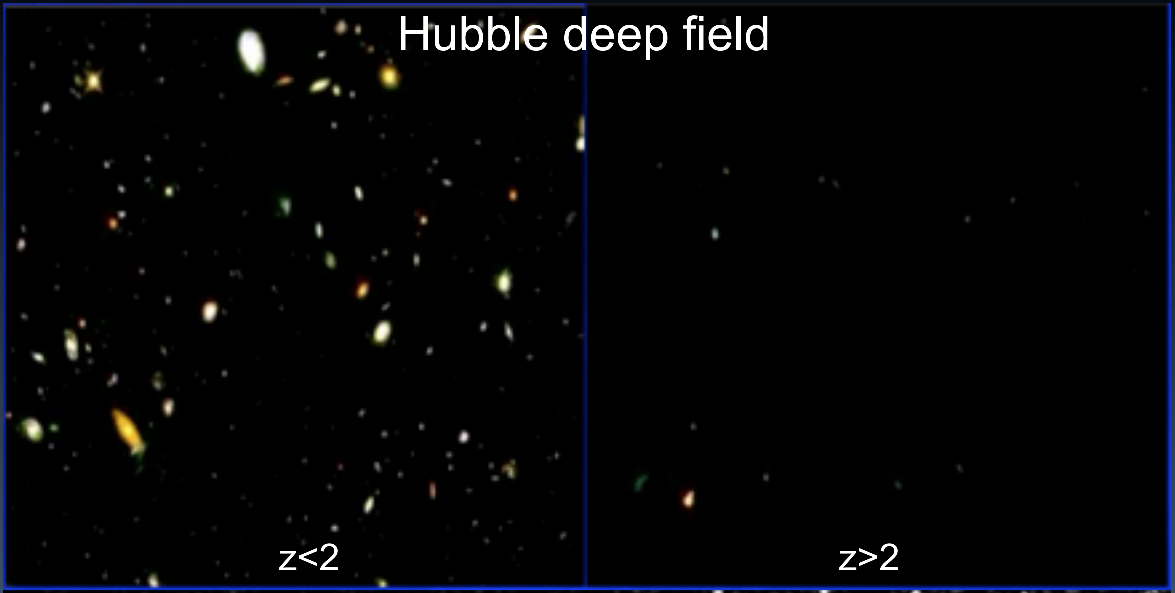
HCN more useful than CO as a star formation tracer?

star formation efficiencies & modes of star formation?

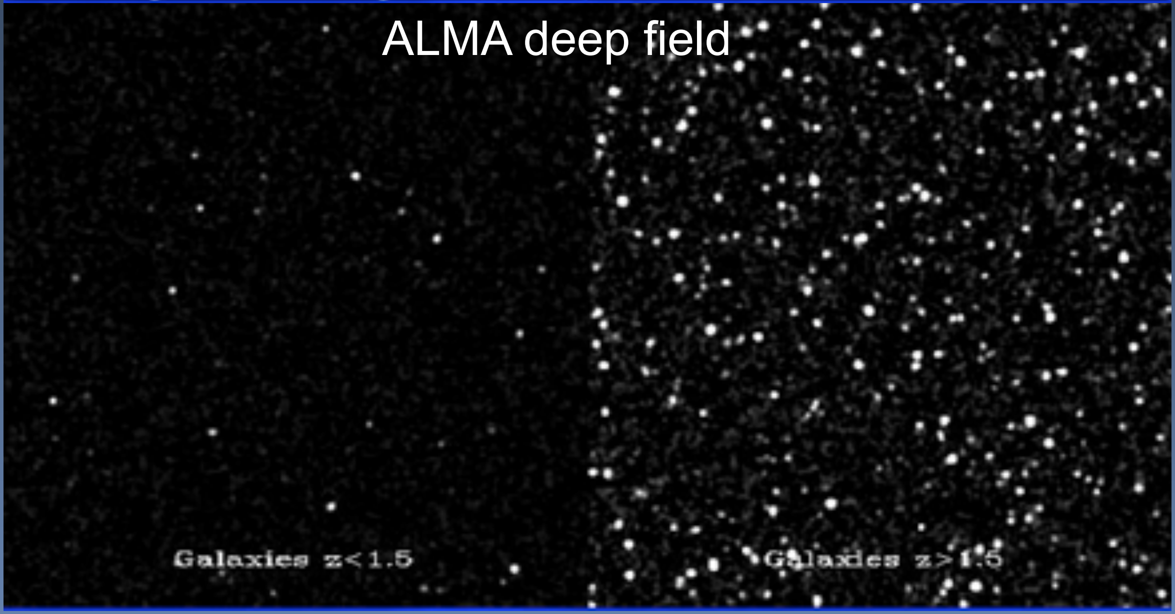
diagnostics of feedback and galactic structure formation: PDR chemistry, XDR chemistry

CO outflows??

ALMA will allow larger samples of galaxies to be studied

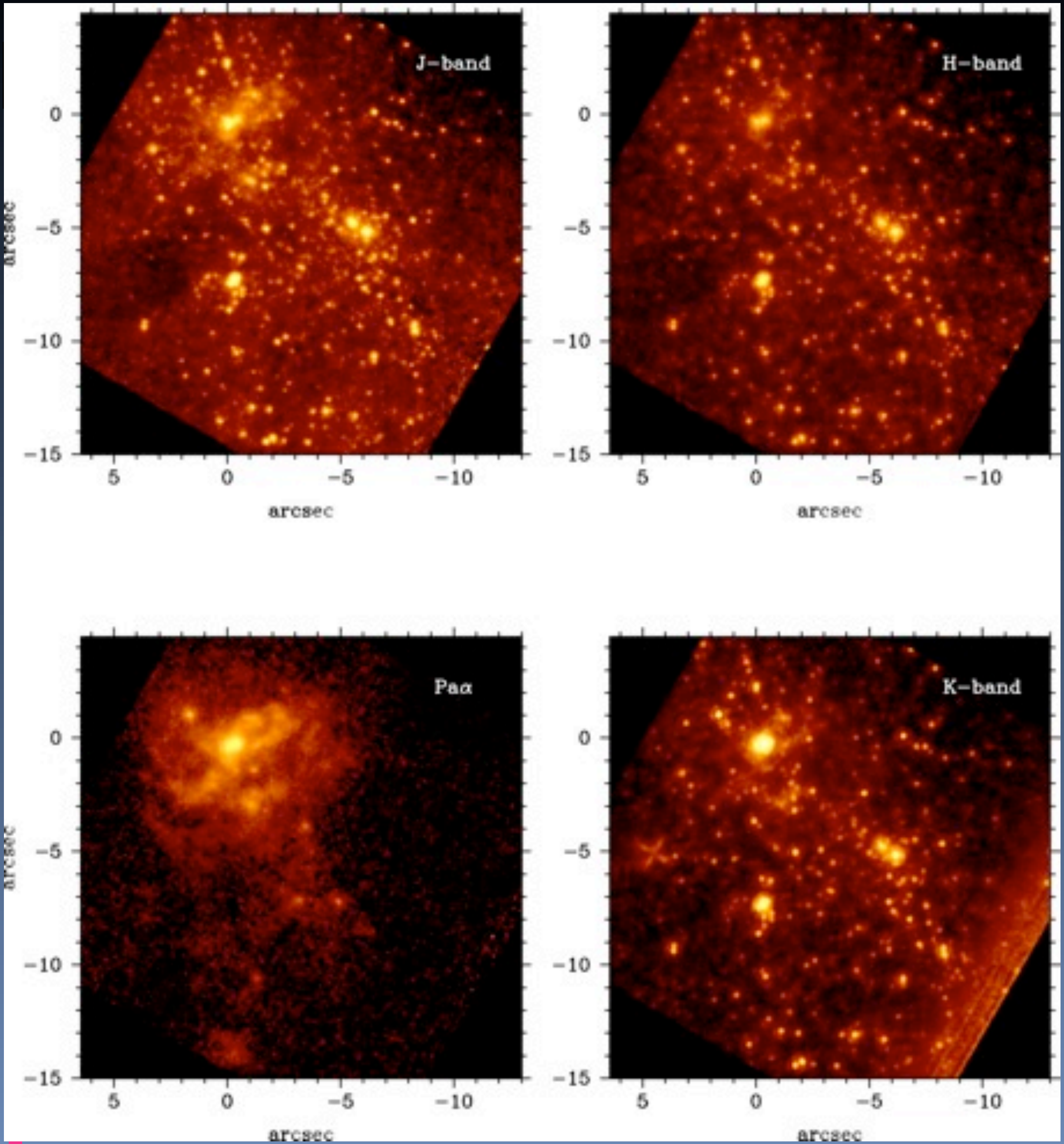


Hubble deep field



ALMA deep field

a possible globular cluster in the making...



NGC 5253

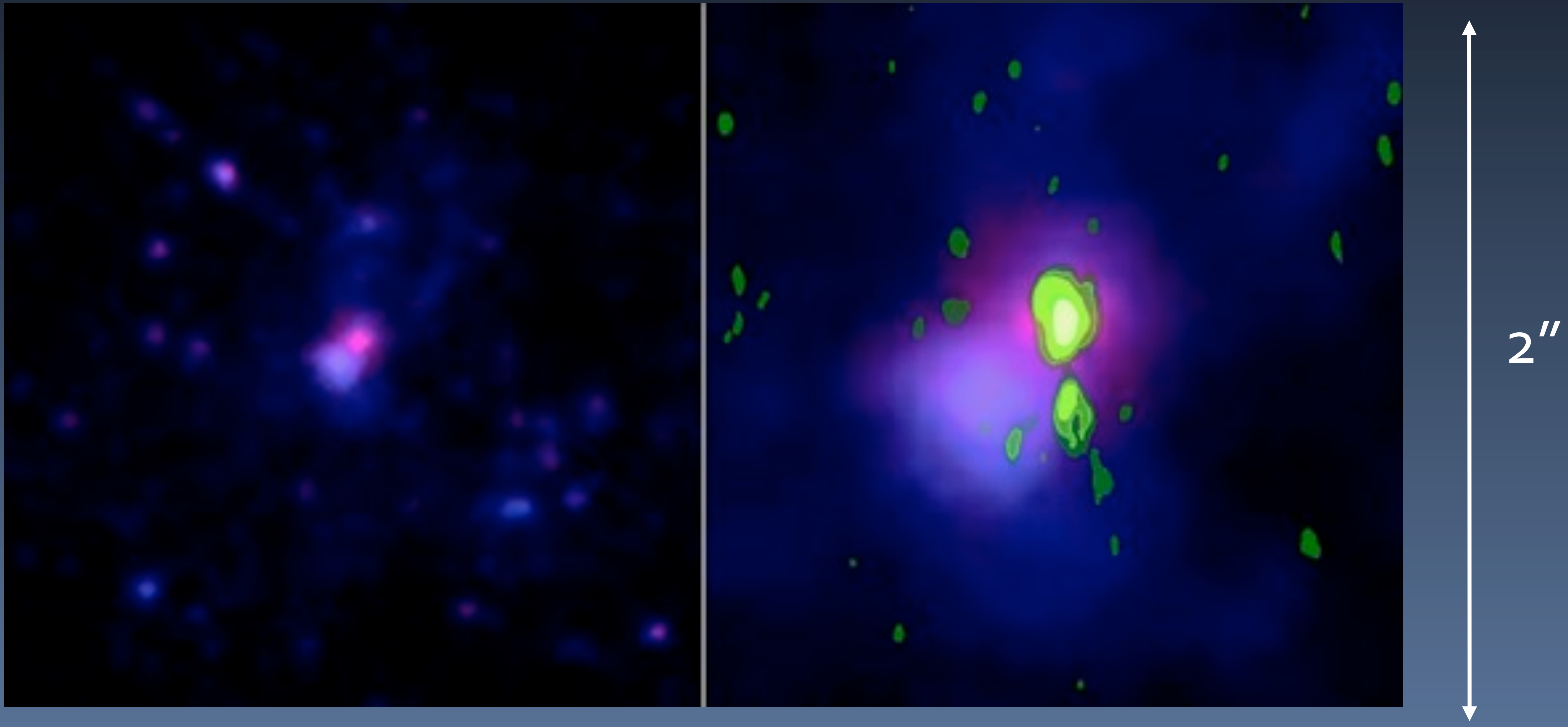
Alonso-Herrero et al. 2004
NICMOS
Turner et al. 2003 Keck

$L = 10^9 L_\odot$
dusty HII region (Av ~16)
diameter 1-2 pc (0.1")
2.5 Myr cluster

cluster first becomes visible at J

at K, dust from the nebula takes over

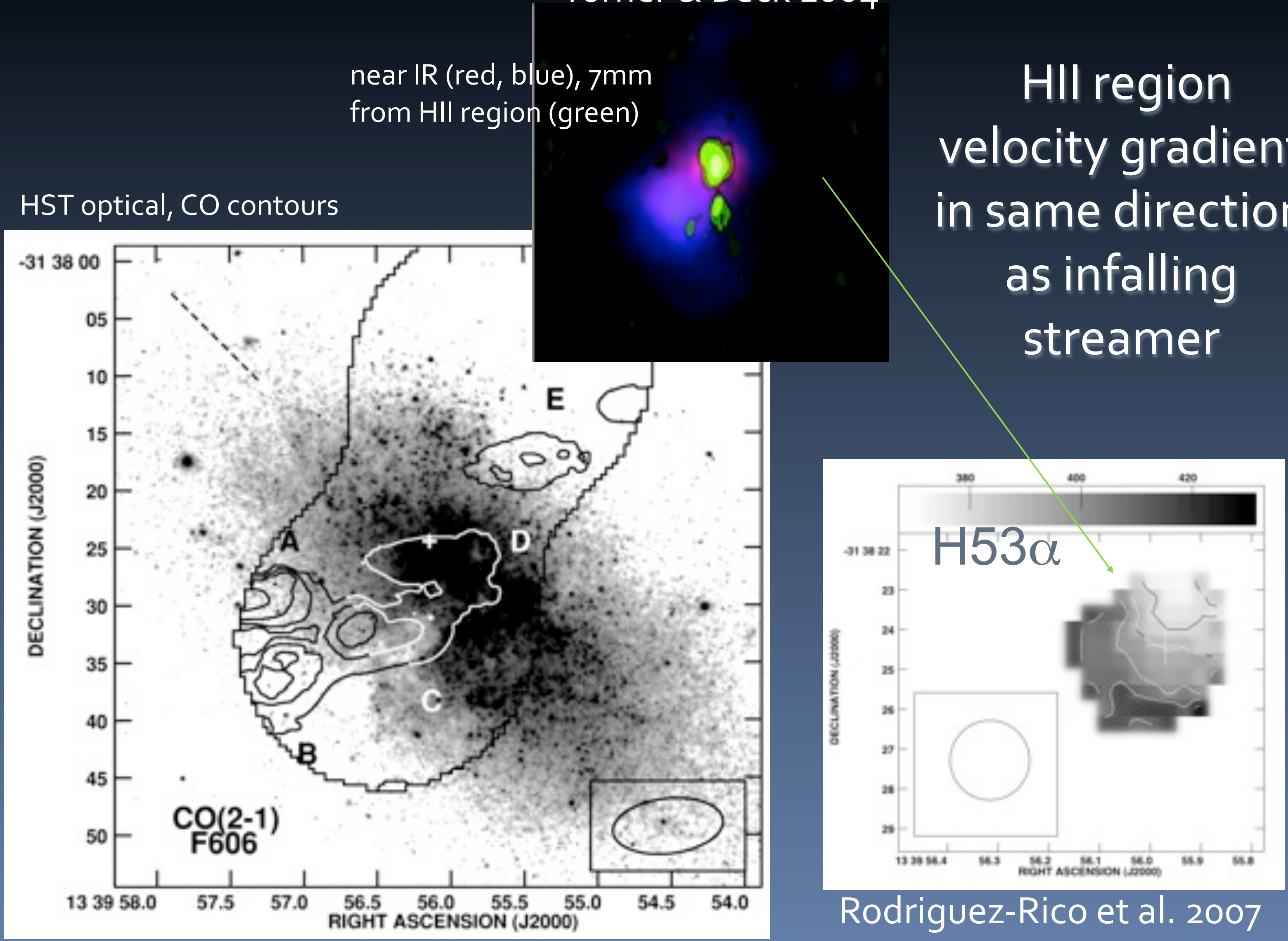
extremely small: super star cluster nebulae in ngc5253



NICMOS J & H

VLA 7mm continuum (“Q” band) 50mas
10^9 L_{sun} in 1 pc radius Turner & Beck 2004, ApJL

accretion trigger



Turner & Beck 2004

near IR (red, blue), 7mm
from HII region (green)

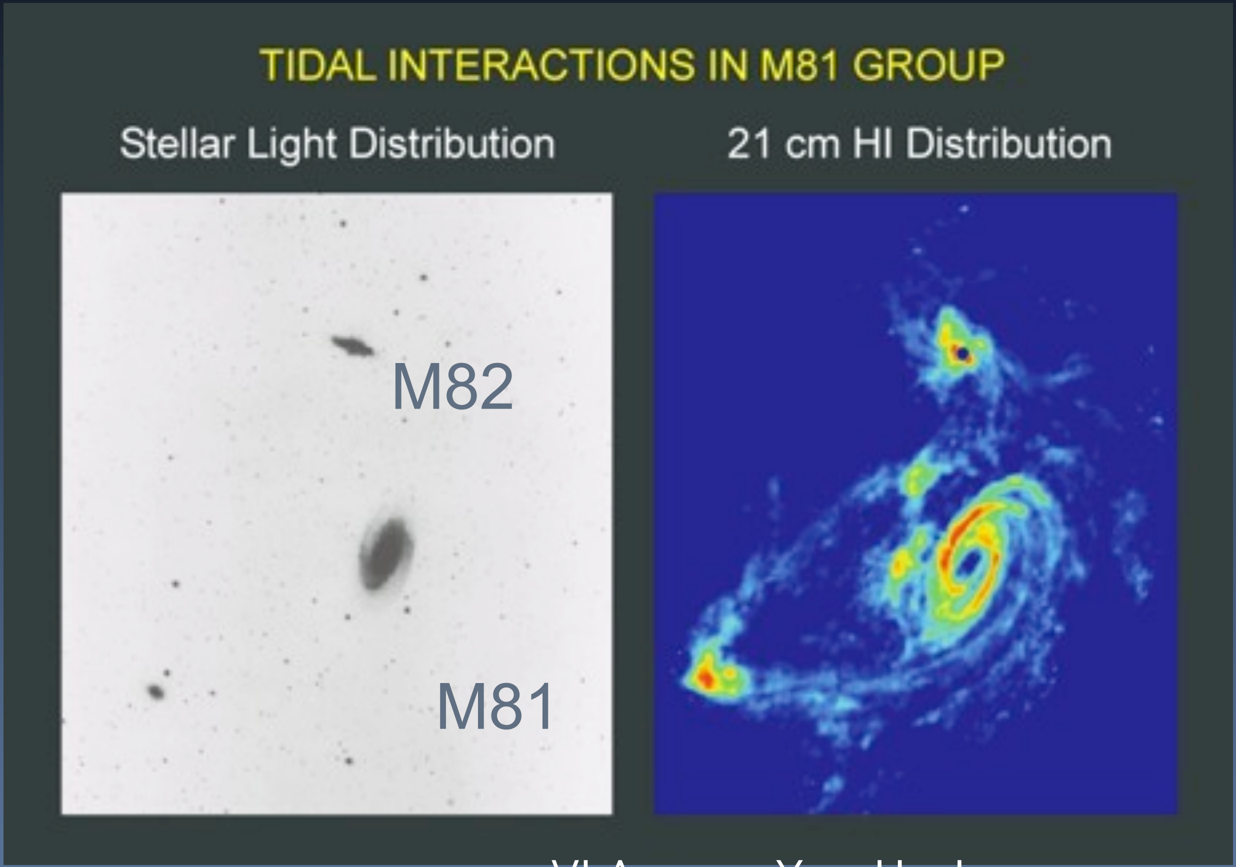
HST optical, CO contours

HII region
velocity gradient
in same direction
as infalling
streamer

CO: Meier et al. 2002

Rodriguez-Rico et al. 2007

gas and extreme star formation



TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

21 cm HI Distribution

VLA 21 cm Yun, Ho, Lo 1994